# Quantifying Spatial and Temporal Vegetation Recovery Dynamics Following a Wildfire Event in a Mediterranean Landscape using EO Data and GIS

Petropoulos, George; Griffiths, Hywel; Kalivas, Dionyssos

*Published in:*
Applied Geography

*DOI:*
10.1016/j.apgeog.2014.02.006

*Publication date:*
2014

*Citation for published version (APA):*
Petropoulos, G., Griffiths, H., & Kalivas, D. (2014). Quantifying Spatial and Temporal Vegetation Recovery Dynamics Following a Wildfire Event in a Mediterranean Landscape using EO Data and GIS. *Applied Geography*, *50*, 120-131. https://doi.org/10.1016/j.apgeog.2014.02.006

Elsevier Editorial System(tm) for Applied Geography
Manuscript Draft

Manuscript Number: JAPG-D-13-00306R3

Title: Quantifying Spatial and Temporal Ecosystem Recovery Dynamics following a wildfire event in a Mediterranean landscape using EO data and GIS Techniques

Article Type: Article

Keywords: Keywords: vegetation regeneration, fires, Landsat TM, ASTER DEM,NDVI,Greece

Corresponding Author: Dr. George Petropoulos,

Corresponding Author's Institution:

First Author: George Petropoulos

Order of Authors: George Petropoulos; Hywel M Griffiths; Dionissios P Kalivas

Abstract: Analysis of Earth Observation (EO) data, often combined with Geographical Information Systems (GIS), allows monitoring of changing land cover dynamics which may occur after a natural hazard such as a wildfire. In the present study, the vegetation recovery dynamics of one such area are evaluated by exploiting freely distributed EO data and GIS techniques. The relationships of re-growth dynamics to the exposure under topographical characteristics of the burn scar are also explored. As a case study, a typical Mediterranean ecosystem in which a wildfire occurred during 2007 is used. Vegetation recovery dynamics of the whole area under the burn scar were investigated based on chronosequence analysis of the normalized difference vegetation index (NDVI) derived from anniversary Landsat TM images. The spatio-temporal patterns of post-fire NDVI on each image date were statistically compared to the pre-fire pattern to determine the extent to which the pre-fire spatial pattern was re-established and the recovery rate. The relationships between NDVI as an expression of recovery rates and aspect were also statistically investigated and quantified using a series of statistical metrics. Results suggested a generally low to moderate vegetation recovery of the local ecosystem five years after the fire event, with the post-fire NDVI spatial pattern generally showing a gradual but systematic return to pre-fire conditions. Re-growth rates appeared to be somewhat higher in north-facing slopes in comparison to south facing ones, in common with other similar studies in Mediterranean type ecosystems. All in all, this study provides an important contribution to the understanding of Mediterranean landscape dynamics, and corroborates the usefulness particularly of NDVI in post-fire regeneration assessment via a well-established methodology presented herein which can also be transferable to other regions. It also provides further evidence that use of EO technology which combined with GIS techniques can offer an effective practical tool for mapping wildfire vegetation dynamics and ecosystem recovery after wildfire.

# Quantifying Spatial and Temporal Vegetation Recovery Dynamics Following a Wildfire Event in a Mediterranean Landscape Using EO Data & GIS


## ABSTRACT

Analysis of Earth Observation (EO) data, often combined with Geographical Information Systems (GIS), allows monitoring of changing land cover dynamics which may occur after a natural hazard such as a wildfire. In the present study, the vegetation recovery dynamics of one such area are evaluated by exploiting freely distributed EO data and GIS techniques. The relationships of re-growth dynamics to the exposure under topographical characteristics of the burn scar are also explored. As a case study, a typical Mediterranean ecosystem in which a wildfire occurred during 2007 is used. Vegetation recovery dynamics of the whole area under the burn scar were investigated based on chronosequence analysis of the normalized difference vegetation index (NDVI) derived from anniversary Landsat TM images. The spatio-temporal patterns of post-fire NDVI on each image date were statistically compared to the pre-fire pattern to determine the extent to which the pre-fire spatial pattern was re-established and the recovery rate. The relationships between NDVI as an expression of recovery rates and aspect were also statistically investigated and quantified using a series of statistical metrics. Results suggested a generally low to moderate vegetation recovery of the local ecosystem five years after the fire event, with the post-fire NDVI spatial pattern generally showing a gradual but systematic return to pre-fire conditions. Re-growth rates appeared to be somewhat higher in north-facing slopes in comparison to south facing ones, in common with other similar studies in Mediterranean type ecosystems. All in all, this study provides an important contribution to the understanding of Mediterranean landscape dynamics, and corroborates the usefulness particularly of NDVI in post-fire regeneration assessment via a well-established methodology presented herein which can also be transferable to other regions. It also provides further evidence that use of EO technology which combined with GIS techniques can offer an effective practical tool for mapping wildfire vegetation dynamics and ecosystem recovery after wildfire.


**Keywords:** *vegetation regeneration, Landsat TM, fires, ASTER DEM, NDVI, Greece*

## 1. INTRODUCTION

Altering land cover dynamics is currently regarded as the single most important variable of global change affecting ecological systems (Otukei and Blaschke, 2010). Wildfires are considered to be one of the most widespread ecological disturbances of natural ecosystems that dramatically affect land cover dynamics at a variety of spatial and temporal scales as a result of the complete or partial removal of vegetation cover (Lhermitte et al., 2011). In this context, knowledge of the spatio-temporal distribution of post-fire vegetation recovery dynamics is of key importance. Such information plays a significant role in various aspects of policy and decision-making as well as in the dynamics and structures of plant and animal communities of the affected ecosystems (Elvira and Hernando, 1989; Gouveia et al., 2010). Knowledge of vegetation recovery dynamics following a fire outbreak is essential to estimate the effects of the fire and to understand the forces driving changes in post-fire ecosystems (Grissino-Mayer and Swetnam, 2000; Casady and Leeuwen, 2009). Such information, if available in a consistent, repetitive and cost-effective manner, is also a crucial element of successful landscape management (Wittenberg et al., 2007). It can assist in identifying areas needing intensive or special restoration programs aiming to reduce soil erosion and runoff, thus mitigating long-term site degradation (Keeley, 2000; Malak and Pausas, 2006; Gouveia et al., 2010). Given that future changes in climate could potentially lead to increases in fire frequency, severity and extend into ecosystems that include species that have not evolved to be able to easily regenerate (Politi et al,. 2009), information on regeneration vegetation is of key importance.

The speed of vegetation recovery can control the extent of various environmental, social, economic and political impacts (Minchella et al., 2009). Indeed, the rate of vegetation biomass re-growth can vary significantly; some areas can show complete vegetation recovery after a few years while others are still not completely recovered decades after the fire. In the Mediterranean region in particular where fire has been an important ecological factor for millennia (Naveh, 1974; Mayor et al., 2007), rates of post-fire recovery dynamics are usually spatially variable and contingent upon a number of factors. This is because of the complexity of landscape structure and the range of responses of such systems to the diverse types of fire regimes. At the landscape level, various studies have shown post-fire regeneration to be mainly dependent on the initial vegetation and site-specific climatic and terrain parameters (Pausas and Vallejo, 1999; Wittenberg et al., 2007). Climatic factors, such as heavy autumn rainfalls, generally also lead to a higher potential for post-fire soil erosion (Millán et al., 1995), which also affect vegetation re-growth dynamics (Pausas et al., 2004). Moreover, various studies have shown that in such environments, post-fire growth is frequently affected by topography and aspect. South-facing slopes experience higher insolation and evapotranspiration rates than north-facing slopes. This results in vegetation tending to grow back more quickly on north-facing slopes with more favourable moisture conditions (Mouillot et al., 2005; Fox et al., 2008). Unfortunately, interactions between such parameters and plant regeneration are poorly known, especially at the scale of a single large fire. At this scale, use of Earth Observation (EO) technology has proved to be a suitable option tool for monitoring plant regeneration after fire.

When combined with Geographic Information Systems (GIS) techniques, EO data have demonstrated promising potential in providing an effective set of tools for analysing and extracting spatial information related to wildfires (Chen et al., 2005; Durduran, 2010; Chen et al., 2011; Kalivas et al., 2013). This integration provides an excellent framework for data capture, storage, synthesis and analysis of acquired spatial data. Indeed, EO data can be combined with GIS and can provide an efficient approach for analysing and extracting spatial information to support decision making reliably and consistently (Chen et al., 2005; Gens, 2010). Both have been used extensively in a range of post-fire applications at different scales of observation; from burnt area mapping (Kokaly et al., 2007; Petropoulos et al., 2011), to mapping changes in soil erosion after fire (Quintano et al., 2006; Mayor et al., 2007; Fox et al., 2008) to evaluating post-fire ecosystem recovery (Segah et al., 2010). The recent advancements in EO technology have made it possible to evaluate patterns of vegetation recovery after wildfires at different spatial, spectral and temporal scales, and a variety of techniques have been developed for this purpose.

Some of the most widely used image analysis approaches employed to characterize the vegetation recovery include image classification (Jakubauskas et al., 1990; White et al., 1996; Viedma et al., 1997; Hall et al., 1991; Steyaert et al., 1997; Stueve et al., 2009), the use of spectral vegetation indices (Diaz-Delgado et al., 2003; Hope et al., 2007; Lhermitte et al., 2011; Chen et al., 2011) and Spectral Mixture Analysis (Smith et al., 2007; Solans Vila and Barbosa, 2010; Veraverbeke et al., 2012). Out of the wide range of techniques available, spectral indices have been used evidently most extensively (Veraverbeke et al., 2010). Their use has largely been based on the hypothesis that the ratio of red (R) to near infrared (NIR) reflectance for green vegetation changes when the foliage containing chlorophyll is destroyed by the fire. Subsequently, the use of a spectral index that is sensitive to the R and NIR regions of the electromagnetic spectrum can be used to identify and potentially quantify vegetation change. The most widely used index for studying regeneration processes is the Normalized Difference Vegetation Index (NDVI, Rouse et al., 1973). NDVI combines the reflectance in the R and NIR spectral region and is a measure of the green vegetation amount. A significant number of studies have utilized this index to monitor post-fire vegetation dynamics, some conducted in Mediterranean climates (Roder et al., 2008; Solans Vila and Barbosa, 2010; Veraverbeke et al., 2010). Also, although a wide range of EO data have been exploited in such studies, it is evident from a review of the literature that imagery from the Landsat series of platforms has been one of the most widely exploited.

Landsat is the only freely-available multispectral satellite high spatial resolution sensor providing a synoptic coverage of the Earth extending back to 1972. Therefore, the value of data from this satellite radiometer is unique and they have been extensively used to monitor the spatial and temporal variations in post-fire vegetation conditions and landscape-scale trends in vegetation dynamics (Hope et al., 2007; Wittenberg et al., 2007; Chen et al., 2011). Landsat spatial resolution allows the detection of both large and small fires and its large sensor field of view allows the observation of several burnt areas in one image. The sensor also has a NIR band which is useful for evaluating vegetation recovery processes (Pereira et al., 1999). Furthermore, its shortwave infrared (SWIR) channels allow highlighting of the internal variability of burnt areas that can be linked to the spatial patterns of damage severity and fire intensity (Justice et al., 1993; Bisson et al., 2008).

Yet, while remote sensing is currently being applied to estimate the vegetation recovery dynamics in different ecosystems, information on the relationships between post-fire recovery and topographic factors is scarce (e.g. Sunee et al., 2001), particularly so in the Mediterranean. This is despite the importance of this issue, as for example identification, at the landscape level, of areas with low recovery dynamics could improve land management and help prioritizing post-fire restoration actions in the fire-affected areas. Results from relevant studies published so far suggest that vegetation recovery dynamics of south-facing slopes can be very different from that of north-facing ones (e.g. Hope et al., 2007; Wittenberg et al., 2007; Fox et al., 2008).

In this context, the main aim of this study has been to assess vegetation recovery dynamics following a fire event using multi-temporal analysis of Landsat Thematic Mapper (TM) images and GIS techniques for a typical Mediterranean characteristics site located in Greece for which a wildfire occurred in 2007. The specific objectives were: first to determine the spatio-temporal patterns of vegetation re-growth dynamics established within the burn scar monitored by the NDVI response and second to analyse the influence of topographical parameters on these dynamics. In this preliminary study, we attempted to fit regression models to the dynamics of the regeneration process and to quantitatively investigate the correlation between post-fire recovery and topographic factors (slope and aspect) using EO data.

## 2. STUDY AREA

The selected study site, Mt. Parnitha, is located approximately 30 km north of the Greek capital Athens (Figure 1). The area covers approximately 200 km$^2$ of land with an altitude ranging from 200-1,400 m above sea level (a.s.l.). The region is covered mainly by Greek Fir (*Abies cephalonica*) and Aleppo Pine (*Pinus halepensis*) forests on the slopes beneath 1,000 m altitude, grasses and shrubs dominate above 1,000m, and under 300m farmlands dominate to the north with suburban housing to the east. The climate is continental, characterised by cold winters and warmer summers. Summer temperatures do not usually exceed 18°C, while in winter temperatures are frequently of around 0°C, (Arianoutsou et al., 2010), with an annual average of 11°C (Ganatsas et al., 2012). Average rainfall in the area is 822 mm (at 1,000 m elevation), with 70 rainy days per year. Snow is also relatively common, with an average of 33 snowy days per year and snow depth averaging 120 cm (Ganatsas et al., 2012).

In the summer of 2007, Greece was hit by the most devastating large fires in its recent history (Kalivas et al., 2013). During the first half of that year average monthly temperatures in the study area increased from 11°C in January 2007 to 26°C in June (NOAA web site, 2013). The maximum monthly temperature in June reached 39°C and there were 12 days in which the temperature rose above 32°C. On June 27th, 2007, at 19:30 local time, a fire, caused by sparks from an overloaded power line, erupted in the area of Dervenohoria, near a village called Stefani, approximately 15 km west of the core of mount Parnitha National Park. On the next day, fanned by a medium strength west wind, it entered the forested western slopes and canyons of the mountain and spread to the summit leaving only charred trees. Its main run stopped when it reached sparse vegetation on the east slope of the mountain in the morning of June 29th. Fought by aerial fire-fighting support, it was controlled three days later (July 1st, 2007). According to official estimates, the total area burnt was in the order of 45 Km$^2$ (Petropoulos et al., 2010).

Mt. Parnitha is a very suitable study site for this type of research from both scientific and practical aspects. First of all, it is one of the few mountains surrounding Athens, the capital of Greece, playing a very important role in the micro-climatic conditions of the capital. Second, due to its rich biodiversity the wider area has been designated as a national park as well as a biodiversity conservation site. It has also been included in the European network of protected areas Natura 2000 EC Habitats Directive, a network of Sites of

Community Importance and Special Areas of Conservation (Arianoutsou et al., 2010). Thus the area has a very significant ecological and aesthetic/recreational value for the local people. Third, the region is characterized by very variable topography characteristics, comprising plain areas and mountainous areas with slopes varying from between 3 % and 90 %, which vary significantly in elevation and aspect. In particular, altitude varies from 200 m.a.s.l to over 1,400 m.a.s.l (the highest elevation being 1,413 m.a.s.l.). Soils in the area are generally shallow and infertile, with the exception of some karstic plateaus, and overly bedrock consisting of sedimentary schists and limestone (Ganatsas et al., 2012). Fourth, all data required were already available from previous works conducted in the region (Petropoulos et al., 2010; 2011; 2012), and as such, the present work also builds on these previous studies conducted in the area.

## 3. DATASETS

Five Landsat TM images (path: 183, row: 33 / raster format) were used in this study to explore the vegetation regeneration dynamics of the selected study region over a period of 5 years, from 2007 to 2011. Images around the same dates ('anniversary dates'; Lillesand and Kiefer, 2000) of different years were selected to circumvent the influence of seasonal differences in both spectral radiation (e.g. Sun elevation angle, Sun–Earth distance, meteorological conditions) and surface reflection. A TM pre-fire image acquired on 16 May 2007 and four post-fire images acquired on 3 July 2007, 24 July 2009, 12 August 2010 and 15 August 2011 were used. All images were obtained from the United Stated Geological Survey (USGS) archive (http://glovis.usgs.gov/) at no cost. They were acquired geometrically corrected, geometrically resampled, and registered to a geographic map projection with elevation correction applied (Level-1T processing).

In addition, the Global Digital Elevation Model (GDEM) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor was used for obtaining topographical information about the study area. The ASTER GDEM product was released in 2009 and was updated (Version 2) at the end of 2011. Estimated accuracies of the product are for 20 meters at 95 % confidence for vertical data and 30 meters at 95 % confidence for horizontal data (ASTER GDEM, 2009). The dataset is provided in geotiff format, in geographic lat/long projection and WGS84/EGM96 datum. It is available to download at no cost from the Earth Remote Sensing Data Analysis Center (ERSDAC) of Japan or the NASA's REVERB (http://reverb.echo.nasa.gov/). ASTER GDEM is distributed as separate tiles of elevation data. Herein, the tile covering the study site was acquired from REVERB.

Last but not least, an estimate of the burnt area was obtained from work that had been carried out previously in the study area. In particular, Petropoulos et al., (2011) obtained a burnt area cartography from the analysis of the same TM post-fire imagery used herein, acquired shortly after the fire extinction (i.e. July 3rd, 2007) by applying a pixel-based classifier based on Support Vector Machines (Vapnik, 1995).

## 4. METHODS

All analysis of the vegetation regeneration for the studied region was carried out using ENVI (v. 5.0, ITT Visual Solutions) and ArcGIS (v. 10.1, ESRI) software platforms. An overview of the methodology implemented is depicted in Figure 2.

### *4.1 Data Pre-processing*

All pre-processing of the spatial datasets were carried out in ENVI. TM images pre-processing entailed a series of steps (Figure 2). First**,** for each date of TM image acquired, each spectral band was imported to ENVI and was converted to top of the atmosphere reflectance (TOA) according to the methodology described by Irons (2011). Subsequently, all the spectral bands from each acquisition date excluding the thermal infrared (i.e. band 6) were layer stacked to form a single image file corresponding to the acquisition date. Then, an empirical line normalization to all images was implemented using the pre-fire Landsat image (acquisition date: May 16$^{th}$ 2007) as a base (ENVI User's Guide, 2008). This is a relative atmospheric correction method which provides an easy way to correct for radiance/reflectance variations due to solar illumination condition, phenology and detector performance degradation (Latifovic et al., 2005). No further topographic correction was necessary as images were already terrain corrected. Next, the slope and aspect maps of the study region were computed from the ASTER GDEM (i.e. elevation map). Subsequently**,** image to image co-registration between the TM images and the ASTER DEM was performed.

In order to analyze imagery from different dates, the data layers must be spatially co-registered so that satellite data are in the same spatial reference frame (Schmidt and Glasser, 1998). The TM pre–fire image was used as a base image to which all other available images were co-registered. Approximately 45 commonly identified ground control points (GCPs) were selected randomly from easily detectable corner points (e.g. road junctions). Image warping was performed by applying the nearest neighbour method, allowing a co-registration of all the images into a common UTM 34N projection under a WGS84 ellipsoid. This resampling method was used to better preserve the digital number (DN)/reflectance values in the original images. To check the co-registration accuracy, the coordinates of 15 additional control points not previously included in the transformation were determined from the base image used. Displacement of these points relative to the other images was examined and results showed a positional accuracy within the sensor pixel range (i.e. < 30 m), which was considered satisfactory.

Then**,** the TM images and the ASTER DEM were layered stacked and subsequently clipped to a smaller area covering an area that included the burn scar and sufficient ample land outside its perimeter. This allowed us to enhance the computational efficiency of the processing that would follow. Next, this dataset was intersected with the burnt area polygon. This last dataset was the one used in analysing the vegetation dynamics occurring within the burn scar area of the Mt. Parnitha region. Some of the datasets derived after the end of pre-processing are illustrated in Figure 3.

### *4.2 Vegetation re-growth mapping*

The approach used to detect the vegetation recovery rate for the fire-affected area for the whole area under the burn scar is shown in Figure 2. Vegetation dynamics of re-growth after the fire was evaluated through multi-temporal analysis of the NDVI. The latter was calculated from the R and NIR bands of each pre-processed TM image using the formula originally proposed by Rouse et al., (1973):

$$NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R} \qquad (1)$$

where $\rho_{NIR}$ and $\rho_R$ denote the near-infrared and the red surface spectral reflectance respectively. NDVI values can in theory scale between -1 and +1. The photosynthetic activity in plants, and their ability to strongly reflect NIR radiation, is expressed by lower reflectance in R and higher reflectance in NIR. As values approach +1, photosynthetic activity becomes very strong. Thus, NDVI is an expression related to the amount of photosyntetically active vegetation exposed to the sensor within each pixel, and typical NDVI values for vegetated areas are in general well above 0.1 (Jensen, 2000; Petropoulos and Kalaitzidis, 2011). Designed to capture the contrast between R and NIR reflection of solar radiation by vegetation, NDVI has been widely used in studies of vegetation phenology dynamics and inter-annual variability of vegetation greenness with different types of EO data including Landsat (Gouveia et al., 2008) and has proved to be particularly useful for monitoring post-fire plant regeneration dynamics (Gouveia et al., 2010).

Following the NDVI computation for each TM image, the derived NDVI layers were layered stacked to the pre-processed dataset (section 4.1) to form a single dataset to facilitate further analysis in the GIS environment. The dynamics of the regeneration process were subsequently analysed by comparing post-fire NDVI spatial patterns to the pre-fire pattern. This allowed determining the extent to which the pre-fire pattern was re-established, and the rate of this recovery. In accordance to previous works (e.g. Hope et al. 2007), descriptive statistics of NDVI within the burn scar were computed from each TM image, which together with scatter plot and non-parametric correlation analysis were used in evaluating the NDVI variations under the burnt area envelope.

In the next step, relationships between vegetation recovery dynamics and aspect were investigated. Aspect analysis was conducted in ArcGIS using the aspect map produced from the ASTER GDEM. In accordance to previous studies (Wittenberg et al., 2007; Fox et al., 2008), pixels with an orientation between NW (315°) and NE (45°) were classified as north facing slopes, whereas south facing slopes were classified those that had an orientation between SE (135°) and SW (225°). Pixels within the burn scar not falling within these value ranges were excluded from this type of analysis. All relevant statistical analyses were performed using SPSS v. 18 software package (SPSS Inc., Chicago, IL).

## 5. RESULTS

Firstly the spatio-temporal patterns of vegetation re-growth dynamics established within the whole burn scar and monitored by the NDVI response were evaluated. Subsequently, the influence of topographical parameters on these dynamics was investigated. In regards to the first step, Figure 4 illustrates the NDVI maps area computed for the whole area under the burn scar and Table 1 provides the corresponding descriptive statistics. Furthermore, several NDVI difference maps were produced to assist in evaluating the spatio-temporal changes in NDVI between both before and just after the fire suppression with the post-fire conditions and all subsequent dates (Figure 5).

A visual comparison of the pre-fire NDVI with the immediate post-fire NDVI maps (Figure 4a and b) clearly shows the regional extend of the destruction of vegetation caused by the fire. This is further evidenced by the abrupt changes in the descriptive statistics of NDVI under the burnt area, when comparing the pre-fire to post-fire conditions. For example, mean NDVI for the area under the burn scar decreased from 0.499 before the fire to 0.087 after the fire. A decrease in the NDVI maximum value after fire suppression is also noticeable (from 0.789 before the fire to 0.309 after the fire) which shows that some of the vegetation inside the burn scar was only partially destroyed by the fire. In terms of vegetation re-growth dynamics for the area, a visual inspection of the post-fire NDVI maps in combination with the associated NDVI descriptive statistics in Table 1 is indicative of vegetation regeneration taking place in the affected area. Clearly, there is a gradual but steady increase in the maximum and mean NDVI within the fire-affected region towards the pre-fire conditions (Figures 4 and 5), which is indicative of vegetation regeneration in the area. Findings also suggest that during the first two years following the fire suppression, regeneration dynamics were higher in comparison to the subsequent years (Figure 4). Also, as can be observed (Figures 4 and 5), different regeneration dynamics are prevailing within the previously burnt area, with stronger dynamics in regeneration particularly at the centre and west area of the fire-affected region in comparison to the rest of the burnt scar area.

In addition, we attempted to fit regression models on the dynamics of the regeneration process. Following other studies (e.g., Hope et al., 2007), scatterplots of the NDVI between pre-fire conditions against subsequent post-fire dates were plotted and slope, intercept and $R^2$ statistics for the regression line plotted through the data were calculated. Figure 6 illustrates the relevant scatterplots produced and Table 2 summarises the statistics relating to those scatterplots. These data clearly mirror the patterns shown by the NDVI change maps and tables, in that they show a very slow regeneration process. Indeed, the movement of the regression line to back towards the 1:1 line with time is very progressive and gradual, and the increase in $R^2$ value for the entire burn scar although small is also clear (Table 2).

As noted earlier, further analysis was concerned with the investigation of the patterns in vegetation regeneration dynamics - as captured from NDVI- to topographic aspect. Table 3 summarises the descriptive statistics for the NDVI across the whole area under the burn scar separately for the north- and south-facing slopes under the burn scar. Figure 7 also illustrates the spatial variation of the NDVI difference between the pre-fire and most recent to today post-fire TM image separately for the south- and north-facing slopes. In common to the analysis conducted earlier, we also attempted to fit regression models to quantitatively investigate the correlation between post-fire recovery dynamics and aspect. As can be observed from these results (Table 4), the general trajectory of regeneration on north-facing slopes and south-facing slopes also appears to be very slow. Yet, some differences are indeed apparent. A greater level of vegetation destruction is evident on north-facing slopes compared to south-facing slopes and the burnt area in general (a decrease in NDVI of 0.43 on north facing slopes compared to 0.39 on south facing slopes and 0.41 on the burn scar in general). Post-fire regeneration seems to be faster on north-facing slopes in comparison to south-facing slopes. For example, mean NDVI on north-facing slopes increased from 0.09 to 0.30 between July 2007 and July 2009 and then to 0.34 in August 2011, after a very slow period with no real increase in NDVI between July 2009 and August 2010. On south facing slopes the increase appears lower, from 0.09 to 0.22 between July 2007 and July 2009 and then to 0.25 in August 2011. The percentage increase in regenerated vegetation by August 2010 was similar on north- and south-facing slopes. On the north-facing and south-facing subsets, the highest regeneration was observed in the period immediately following the fire (July 2007-July 2009). After very slow (if not negligible) regeneration between July 2009 and August 2010, the rate of vegetation regeneration then increased during the most recent time period. These data also confirm the faster regeneration on north-facing slopes compared to south-facing slopes, with higher slopes and $R^2$ values in all cases ($R^2$ values of scatterplots on north-facing slopes were double that of south-facing slopes for the two most recent time intervals).

## 6. DISCUSSION

The results presented here indicate the large degree of spatial variability in terms of vegetation regeneration in the study region. They also underline the significance of wildfires such as that occurred on Mt. Parnitha as agents of vegetation destruction and modifiers of the landscape. Results also clearly show that vegetation regeneration in the affected area is a process that can potentially take a long time. Indeed, four years after the fire the landscape had still not reached pre-fire vegetation coverage; in fact NDVI levels had only just passed half their original pre-fire levels. This is in common with previous studies of the fire regeneration of vegetation on Mount Parnitha and Mount Taygetos in Greece (Arianoutsou et al., 2010). Yet, those contrast those reported by Wittenberg et al., (2007) who showed that vegetation had recovered to pre-fire conditions within five years in Mount Carmel, Israel, even following multiple fires. The fact that the greatest regeneration was observed during a two year interval may be significant when comparing to lower regeneration during subsequent time intervals which were only one year long, or this pattern could reflect the rapid regrowth of vegetation immediately following the fire, and more gradual vegetation regrowth during subsequent periods as soil and hydrological characteristics improved.

Arianoutsou et al (2010) found that the recovery for tree species (*Abies cephalonia* and *Pinus nigra*) was likely to be slow in general, with some localised differences in common with fire-disturbed ecosystems elsewhere in the Mediterranean (Southern Spain – Clemente et al., 2006 and Mayor et al., 2007; Portugal - Gouveia et al., 2010), in the United States (Chen et al., 2011) and Indonesian Borneo (Hoscilo et al, 2013). The concentration of dark green regions (indicating higher NDVI) in the central areas of the burn scar region in 2009, 2010 and 2011 (Figure 4) and the orange and red areas in Figure 5 and Figure 7 (indicating greater regeneration) indicate that vegetation regeneration was focused to a greater extent on these areas. This point to a spatial heterogeneity in vegetation and landscape response as a result of more localized factors. This more complex pattern of vegetation regeneration is also in good agreement with many studies (e.g. Inbar et al., 1998) reporting very fast regeneration rates within the first two years following wildfires and many other authors finding that regeneration was faster on north-facing slopes compared to south-facing slopes (e.g. Inbar et al., 1998; Pausas and Vallejo, 1999; Cerdá and Doerr, 2005; Fox et al., 2008).

Many studies (e.g. Gouveia et al., 2008, 2009) have identified that water availability is a major limiting factor on fire frequency and regeneration because vegetation is generally more dense in wetter areas compared to drier areas (Gouveia et al., 2010). In Greece, as well as the wider Mediterranean region, some studies suggest that hydrological changes (e.g. more frequent droughts) could lead to an increased frequency of fires similar to that of June 2007 and that forest fires are increasingly occurring in higher latitude areas and at higher altitudes, where the forest species, in contrast to those growing at lower altitudes and latitudes in the Mediterranean regions, have not developed a regenerative response to regular disturbance by fire (Arianoutsou et al., 2010; Retana et al., 2012). If this is the case, then it is likely that it will be increasingly difficult for landscapes to recover to pre-fire conditions as the recovery process has been shown to be relatively long. As the present work has shown, the Mt. Parnitha burn scar area had not recovered to half its pre-fire vegetation levels within four years. If this region suffered further fires, then the resilience and sustainability of this economically and culturally valuable ecosystem would inevitably be threatened as has been shown in other regions of Greece (Christakopoulos et al., 2007).

One of the key factors that need to be considered when planning for the effects of such wildfires is the species composition of the ecosystems. Ganatsas et al., (2012) and Arianoutsou et al., (2010) have both demonstrated that the slow regeneration of vegetation (especially *A. cephalonia*) on the burn scar in Mt. Parnitha is, in part, due to the fact that they are obligate seeders whose seeds ripen in August. These seeds may be destroyed during summer wildfires and as such will not be able to regenerate. Ecosystem recovery in forests dominated by these species is then likely to be dominated by scrubland species, rather than the original forest species. This pattern was observed by Crotteau et al., (2013) in the southern Cascades, USA, where regions which had high-severity burns were dominated by greater shrub coverage. Puerta-Piñero et al. (2010) showed that long-standing, stable forest areas display faster regeneration than younger forests. The implications of this for the long term sustainability of these types of ecosystems in a future of more frequent fires are significant since forests may not be allowed the time to develop into stable communities that are able to recover quickly. The resilience of these ecosystems, will, therefore, be significantly reduced under a regime of increased fire frequency (Diaz-Delgado et al., 2002).

In common with analogous studies conducted elsewhere (e.g. on the Iberian Peninsula – Pausas and Vallejo, 1999, Cerdá and Doerr, 2005; SE France – Fox et al., 2008; Mt. Carmel, Israel - Kutiel, 1994, Inbar et al. 1998; Wittenberg et al. 2007) it is also clear that aspect is a key control on the rate of vegetation regeneration. It is likely that this reflects the local effects of microclimate on hydrological processes which play an important role in triggering vegetation re-growth. Such differences in post-fire regeneration can both reflect and influence localised hydrological variability through soil hydrophobicity (Cerdá and Doerr, 2005) and changes in overland flow patterns and soil erosion, especially through destroying protective vegetation and litter on the forest floor (Shakesby and Doerr, 2006). Mayor et al., (2007) showed that sediment yield and runoff in an unburned catchment in Spain were considerably less than in burned catchments, for six years following a wildfire. In small, upland catchments in particular, this may have significant impacts on flood risk.

This study has focused on changes in land cover over a relatively short period (2007-2011). However, it is recognised that post-fire ecosystem recovery is historically contingent and can be a function of pre-fire forest cover, land-use, species composition and fire history (Gouveia et al., 2010; Puerta-Piñero et al., 2010) and more long term land cover and fire history is needed in order to fully understand ecosystem dynamics (Chen et al., 2011). Analysis of historical maps, aerial photography and other documentary evidence may augment the high resolution spatial data provided by EO data. Historical reconstructions, similar to that performed by Korb et al., (2012) in south west Colorado, USA, can be particular useful when compared with more recent data. One of the principal areas in which EO could be deployed in this field is through the remote sensing of soil moisture (Bourgeau-Chavez et al., 2007). In addition, it would be instructive to complement the inter-annual measurements of regeneration provided by EO data with intra-annual and seasonal data in order to provide a more complete picture of land cover dynamics following wildfires (Lhermitte et al., 2011). At this point, it is also worthwhile to note that it was not possible to quantify uncertainties in the DEM used to derive the topographical information for the study area (elevation, slope, aspect), and included herein. As such, potential inaccuracies in the predictions of these parameters and their relationships to the ecosystem recovery dynamics identified in the area could not be incorporated in the analysis and the results interpretation. Results are, however, in line with other studies examining the relationships between post-fire vegetation recovery and topographic parameters (Díaz-Delgado et al., 2003; Wittenberg et al., 2007; Fox et al., 2008), which also did not conduct any kind of analysis to examine such relationships.

Accurate assessments of vegetation recovery in burnt areas requires not only a qualitative analysis (species, communities), but also the determination of abundance (vegetation cover, Leaf Area Index, biomass). The results of this study imply that routine assessment of a restoration process can be possible from the synergy of EO and GIS, providing that suitable imagery is available at no cost and at regular time intervals. As wildfires in Mediterranean areas and similar ecosystems across the globe are causing significant changes to land cover and pose a serious threat to ecosystem resilience, the complex, multi-scale cooperation required to effectively plan for, and manage the effects of these fires (described by Morehouse et al., 2011) can be aided by the use of EO data such as Landsat data. Such analysis, should, evidently, be combined with ground-truthed high-resolution (both spatial and temporal) ecological surveys wherever possible. Images acquired at annual (or even sub-annual) resolution would be ideal as it would enable us to adequately factor seasonal and phenological factors in to the analyses. Such analyses would allow us to obtain a more detailed understanding of the response of such critical ecosystems to disturbance by fire. In a future of increased wildfire frequency as a result of climate change, such information is essential for ensuring landscape and ecosystem sustainability.

In conclusion, it should be noted that the present study has focused on exploring vegetation re-growth based on the use of NDVI but without distinguishing between different vegetation types in the regeneration dynamics. This can be considered as a downside of the approach followed herein, given that knowledge of vegetation types and conditions is required to better understand and interpret the nature of the wildland fire damage (Milne, 1986). Yet, NDVI is a parameter that can provide information on vegetation green biomass amount, which essentially is what is needed when decision need to be taken in forest management and planning, thus making it a very useful tool from a practical point of view (Malak and Pausas, 2006). Furthermore, it will be interesting in future work to explore the spatio-temporal relationships of vegetation re-growth with other factors, such as the type of the actual fuel burnt, slope angle or soil type.

## 7. CONCLUSIONS

In this study an analysis of vegetation recovery dynamics in a Mediterreanean ecosystem of high environmental and socio-economical importance impacted by a significant wildfire based on the analysis of multiple Landsat TM images was presented. These EO data were integrated in a GIS framework to enable the analysis of changes in NDVI on a burn scar on Mount Parnitha, Greece, on four dates following the fire that occurred on June 2007. These changes enabled us to assess the regeneration of the ecosystem after the fire and to also explore the spatio-temporal variation of vegetation regeneration dynamics in respect to topographic aspect.

Results suggested a very slow post-fire recovery, with the post-fire NDVI spatial pattern showing a relatively rapid regeneration in the two years following the fire, but becoming more gradual in subsequent years. It appears that vegetation in the fire-affected area has not yet reached pre-fire conditions and results suggest that it may take a number of years for this to occur. Interestingly, results suggested as well that north-facing slopes exhibited a slightly faster rate of recovery compared to south-facing slopes. This might be due to more favourable micro-climatic and hydrological conditions for vegetation growth in these areas. In this respect, similar findings have been reported by other investigators examining the effect of topography on post-fire vegetation regeneration in Mediterranean ecosystems and elsewhere.

An understanding of the spatial patterns of vegetation re-growth dynamics in fire-affected areas can assist to better appreciate post-fire landscape processes, which can subsequently aid restoration actions in the affected region. In addition, the present study contributes to the understanding of Mediterranean landscape dynamics, and corroborates the usefulness of NDVI in post-fire regeneration assessment. Last but not least, it confirms that EO technology and GIS analysis techniques can provide a potentially operational solution to support local studies of land cover restoration after wildfires, provided that satellite imagery can be acquired at regular time intervals over a given region.


## Acknowledgments

Authors wish to thank the United Stated Geological Survey (USGS) for the free access to the Landsat TM satellite images. Dr. Petropoulos is thankfulness to the Greek Scholarships Foundation (IKY) for supporting this work. Authors also express thanks Mr. Anthony Smith from Aberystwyth University for his help with the figures preparation included in the manuscript.


**REFERENCES**


Arianoutsou, M., Christopoulou, A., Kazanis, D., Tountas Th, G. E., Bazos, I., & Kokkoris, Y. (2010). Effects of fire on high altitude coniferous forests of Greece. In *6th international conference of wildland fire, Coimbra*.

ASTER GDEM (2009). ASTER GDEM Version. 1. Readme File http://www.gdem.aster.ersdac.or.jp [accessed on July 24th, 2011].

Bisson, M., Fornaciai, A., Coli, A., Mazzarini, F., & Pareschi, M. T. (2008). The vegetation resilience after fire (VRAF) index: development, implementation and an illustration from central Italy. *International Journal of Applied Earth Observation and Geoinformation*, *10*(3), 312-329.

Bourgeau-Chavez, L. L., E. S. Kasischke, K. Riordan, S. Brunzell, M. Nolan, E. Hyer, J. Slawski, M. Medvecz, T. Walters, & S. Ames (2007). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *International Journal of Remote Sensing 28* (10), 2133-2162.

Casady, G.M., W.J.D. Leeuwen, S.E. Marsh (2009). Evaluating post-wildfire vegetation regeneration as a response to multiple environmental determinants. *Environmental Model Assessment*, *15* (5), 295-307.

Cerdá, A., & Doerr, S. H. (2005). Influence of vegetation recovery on soil hydrology and erodibility following fire: an 11-year investigation. *International Journal of Wildland Fire*, *14*(4), 423-437.

Chen, S. S., Chen, L. F., Liu, Q. H., Li, X., & Tan, Q. (2005). Remote sensing and GIS-based integrated analysis of coastal changes and their environmental impacts in Lingding Bay, Pearl River Estuary, South China. *Ocean & coastal management*, *48*(1), 65-83.

Chen, X., Vogelmann, J. E., Rollins, M., Ohlen, D., Key, C. H., Yang, L., Huang, C. & Shi, H. (2011). Detecting post-fire burn severity and vegetation recovery using multitemporal remote sensing spectral indices and field-collected composite burn index data in a ponderosa pine forest. *International Journal of Remote Sensing*, *32*(23), 7905-7927.

Christakopoulos, P., Hatzopoulos, I., Kalabokidis, K., Paronis, D., & Filintas, A. (2007) Assessment of the response of a Mediterranean-type forest ecosystem to recurrent wildfires and to different restoration practices using Remote Sensing and GIS techniques. *Proceedings of the 6th international workshop of the EARSel special interest group on forest fires*, 213-216.

Clemente, R. H., Cerrillo, R. M., Bermejo, J. E., & Gitas, I. Z. (2006). Modelling and monitoring post-fire vegetation recovery and diversity dynamics: A diachronic approach using satellite time-series data set. *Forest ecology and management*, *234*, S194.

Crotteau, J. S., Varner III, M., & Ritchie, M. W. (2013). Post-fire regeneration across a fire severity gradient in the southern Cascades. *Forest Ecology and Management*, *287*, 103-112.

Díaz-Delgado R., Lloret F, Pons X., &Terradas J. (2002). Satellite evidence of decreasing resilience in Mediterranean plant communities after recurrent wildfires. *Ecology, 83*, 2293-2303.

Diaz-Delgado, R., Lloret, F., & Pons, X. (2003). Influence of fire severity on plant regeneration through remote sensing imagery. *International Journal of Remote Sensing*, *24*(8), 1751–1763.

Durduran, S.S. (2010). Coastline change assessment on water reservoirs located in the Konya Basin Area, Turkey, using multitemporal Landsat imagery, *Environmental Monitoring and Assessment*, *164*, 453–461.

Elvira, L.M., & Hernando, C. (1989). Inflamabilidad y energia de las especies de sotobosque (estudio piloto con aplicación a los incendios forestales). Monografias INIA nº 68, Ministerio de Agricultura Pesca y Alimentacion. Madrid.

Fox, D. M., Maselli, F., & Carrega, P. (2008). Using SPOT images and field sampling to map burn severity and vegetation factors affecting post forest fire erosion risk. *Catena*, *75*(3), 326-335.

Ganatsas, P., Daskalakou, E., & Paitaridou, D. (2012). First results on early post-fire succession in an Abies cephalonica forest (Parnitha National Park, Greece). *iForest-Biogeosciences and Forestry*, *5*(1), 6.

Gens, R. (2010). Remote sensing of coastlines: detection, extraction and monitoring. *International Journal of Remote Sensing*, *31*(7), 1819-1836.

Gouveia, C., DaCamara, C. C., & Trigo, R. M. (2010). Post-fire vegetation recovery in Portugal based on spot/vegetation data. *Natural Hazards and Earth System Science*, *10*(4), 673-684

Gouveia, C., Trigo, R. M., & DaCamara, C. C. (2009). Drought and vegetation stress monitoring in Portugal using satellite data. *Natural Hazards and Earth System Science*, *9*(1), 185-195.

Gouveia, C., Trigo, R. M., DaCamara, C. C., Libonati, R., & Pereira, J. M. C. (2008). The North Atlantic Oscillation and European Vegetation Dynamics, *Int. J. Climatol., 28*(14), 1835–1847.

Grissino-Mayer, H. D., & Swetnam, T. W. (2000). Century-scale climate forcing of fire regimes in the American Southwest. *Holocene*, *10*(2), 213–220.

Hall, F., Botkin, D., Strebel, D., Woods, K., & Goetz, S. (1991). Large-scale patterns of forest succession as determined by remote sensing. *Ecology, 72*, 628–640.

Hope, A., Tague, C., & Clark, R. (2007). Characterizing post-fire vegetation recovery of California chaparral using TM/ETM+ time-series data. *International Journal of Remote Sensing*, *28*(6), 1339-1354.

Hoscilo, A., Tansey, K. J., & Page, S. E. (2013). Post-fire vegetation response as a proxy to quantify the magnitude of burn severity in tropical peatland. *International Journal of Remote Sensing*, *34*(2), 412-433.

Inbar, M., Tamir, M., & Wittenberg, L. (1998). Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. *Geomorphology*, *24*(1), 17-33.

Irons, J. 2011. Landsat 7 science data user's handbook, Report 430-15-01-003-0. National Aeronautics and Space Administration, http://landsathandbook.gsfc.nasa.gov/ [accessed on July 10th, 2013].

Jakubauskas, M. E., Lulla, K. P., & Mausel, P. W. (1990). Assessment of vegetation change in a fire-altered forest landscape. *PE&RS, Photogrammetric Engineering & Remote Sensing*, *56*(3), 371-377.

Jensen, J. R., (2000). Remote Sensing of the Environment: An Earth Resource Perspective. Saddle River, N.J, Prentice Hall:.

Justice, C.O., Malingreau, J.P., & Setzer, A.W., (1993). Satellite remote sensing of fire: potential and limitation. In: Crutzen, P., & Goldhammer, J. (Eds.), *Fire in the Environmental: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires* (pp. 77–88.). New York, John Wiley and Sons

Kalivas, D., Petropoulos, G.P., Athanasiou, I. % V. Kollias (2013). An intercomparison of burnt area estimates derived from key operational products: analysis of Greek wildland fires 2005-2007. *Nonlinear Processes in Geophysics*, *20*, 1-13.

Keeley, J. E. (2000). Chaparral. In: M. G. Barbour, & W. D. Billings (Eds.), *North American terrestrial vegetation* ( pp. 204–253). New York: Cambridge University Press.

Kokaly, R. F., Rockwell, B. W., Haire, S. L., & King, T. V. (2007). Characterization of post-fire surface cover, soils, and burn severity at the Cerro Grande Fire, New Mexico, using hyperspectral and multispectral remote sensing. *Remote Sensing of Environment*, *106*(3), 305-325.

Korb, J. E., Fulé, P. Z., & Stoddard, M. T. (2012). Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA. *Forest Ecology and Management*, *269*, 10-18.

Kutiel, P. (1994). Fire and ecosystem heterogeneity: a Mediterranean case study. *Earth Surface Processes and Landforms*, *19*(2), 187-194.

Latifovic, R., Fytas, K., Chen, J. & Paraszczak, J., (2005). Assessing land cover change resulting from large surface mining development, *International Journal of Applied Earth Observation and Geoinformation*, 7(1), 29-48.

Le Houérou, H. N., Bingham, R. L., & Skerbek, W. (1988). Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. *Journal of arid Environments*, *15*(1), 1-18.

Lhermitte, S., Verbesselt, J., Verstraeten, W. W., Veraverbeke, S., & Coppin, P. (2011). Assessing intra-annual vegetation regrowth after fire using the pixel based regeneration index. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66*(1), 17-27.

Lillesand T. M. & Kiefer R. W., (2000). *Remote Sensing and Image Interpretation*, (4th ed.), Chichester, Wiley & Sons.

Malak, D A., and J. G. Pausas (2006). Fire regime and post-fire NOrmalised Difference Vegetation Index changes in the eastern Iberain peninsula (Mediterranean basin). *Intern. Journal of Wildland Fire*, *15*, 407-413.

Mayor, A. G., Bautista, S., Llovet, J., & Bellot, J. (2007). Post-fire hydrological and erosional responses of a Mediterranean landscpe: Seven years of catchment-scale dynamics. *Catena*, *71*(1), 68-75.

Millán, M.M., Estrela, M.J., & Caseller, V., 1995. Torrential precipitations on the Spanish east coast: the role of the Mediterranean sea surface temperature. *Atmos. Res. 36*, 1–16.

Milne, A.K. (1986). The use of remote sensing in mapping and monitoring vegetational change associated with bushfire events in eastern Australia. *Geocarto International*, *1*, 25-32.

Minchella, A., F. Del Frate, F. Capogna, S. Anselmi, F. Manes (2009). Use of multitemporal SAR data for monitoring vegetation recovery of Mediterranean burned areas. *Remote Sensing and Environment*, *113*(3), 588-597.

Morehouse, B. J., Henderson, M., Kalabokidis, K., & Iosifides, T. (2011). Wildland Fire Governance: Perspectives from Greece. *Journal of Environmental Policy & Planning*, *13*(4), 349-371.

Mouillot, F., Ratte, J. P., Joffre, R., Mouillot, D., & Rambal, S. (2005). Long-term forest dynamic after land abandonment in a fire prone Mediterranean landscape (central Corsica, France). *Landscape Ecology*, *20*(1), 101-112.

National Oceanic and Atmospheric Administration (NOAA), 2007. http://www.ncdc.noaa.gov/cdo-web/datasets/GHCNDMS/stations/GHCND:GR000016716/detail [accessed on October 4th, 2013].

Naveh, Z. (1974). Effects of fire in Mediterranean Region. In: Kozlowsky, T.T., Ahlgren, C.E. (Eds.), *Fire Ecosystems* (pp. 401–434.), New York, Academic Press,

Otukei, J. R., & Blaschke, T. (2010). Land cover change assessment using decision trees, support vector machines and maximum likelihood classification algorithms. *International Journal of Applied Earth Observation and Geoinformation*, *12*, S27-S31.

Pausas J.G., Ribeiro E., & Vallejo, R. (2004). Post-fire regeneration variability of Pinus halepensis in the eastern Iberian Peninsula. *For Ecol Manag 203*,251–259.

Pausas, J. G., & Vallejo, V. R. (1999). The role of fire in European Mediterranean ecosystems. In Chivieco, C. (Ed.) *Remote Sensing of Large Wildfires in the European Mediterranean Basin* (pp. 3-16), Berlin Heidelberg Springer..

Pereira, J. M., Sá, A. C., Sousa, A. M., Silva, J. M., Santos, T. N., & Carreiras, J. M. (1999). Spectral characterization and discrimination of burnt areas. In: Chuvieco (Eds.), *Remote Sensing of Large Wildfires in the European Mediterranean Basin*. Sprinter-Verlag, Berlin/Heidelberg, pp. 122–138.

Petropoulos G.P. and C. Kalaitzidis (2011). Multispectral vegetation indices in remote sensing: an overview – book chapter. In “Ecological Modeling”, Chapter 2, 15-39, Novapublishers, USA, ISBN: 978-1-61324-567-5

Petropoulos, G., K.P. Vadrevu, G. Xanthopoulos, G., Karantounias and M. Scholze (2010). A Comparison of Spectral Angle Mapper and Artificial Neural Network Classifiers Combined with Landsat TM Imagery Analysis for Obtaining Burnt Area Mapping. Sensors, 10, 1967-1985.

Petropoulos, G. P., Kontoes, C., & Keramitsoglou, I. (2011). Burnt area delineation from a uni-temporal perspective based on Landsat TM imagery classification using Support

Vector Machines. *International Journal of Applied Earth Observation and Geoinformation*, *13*(1), 70-80.

Petropoulos, G.P., C. C. Kontoes, and I. Keramitsoglou (2012). Land cover mapping with emphasis to burnt area delineation using co-orbital ALI and Landsat TM imagery. *International Journal of Applied Earth Observation and Geoinformation*, *18*, 344-355.

Politi, P. I., Arianoutsou, M., & Stamou, G. P. (2009). Patterns of *Abies cephalonica* seedling recruitment in Mount Aenos National Park, Cephalonia, Greece. *Forest Ecology and Management*, *258*(7), 1129-1136.

Puerta-Piñero, C., Sánchez-Miranda, A., Leverkus, A., & Castro, J. (2010). Management of burnt wood after fire affects post-dispersal acorn predation. *Forest Ecology and Management*, *260*(3), 345-352.

Quintano, C., Fernandez-Manso, A., Fernandez-Manso, O., & Shimabukuro, Y.E., (2006). Mapping burnt areas in Mediterranean countries using spectral mixture analysis from a uni-temporal perspective. *International Journal of Remote Sensing*, *27*, 4, 645-662.

Retana, J., Arnan, X., Arianoutsou, M., Barbati, A., Kazanis, D., & Rodrigo, A. (2012). Post-fire management of non-serotinous pine forests. In Moreira, F., Arianoutsou, M., Corona, P., & De las Heras, J. (Eds.). *Post-Fire Management and Restoration of Southern European Forests* (pp. 151-170). Netherlands, Springer..

Roder, A., Hill, J., Duguy, B., Alloza, J. A., & Vallejo, R. (2008). Using long time series of Landsat data to monitor fire events and postfire dynamics and identify driving factors. A case study in the Ayora region (eastern Spain), *Remote Sens. Environ*., 112, 259– 273.

Rouse, J.W., Haas, R.H., Schell, J.A. & Deering, D.W., 1973, Monitoring vegetation systems in the Great Plains with ERTS. In *3rd ERTS Symposium*, NASA SP-351 I, pp. 309–317.

Schmidt, H., & Glasser, C., (1998). Multitemporal analysis of satellite data and their use in the monitoring of the environmental impacts of open cast lignite mining areas in eastern Germany. *International Journal of Remote Sensing 19*, 2245–2260.

Segah, H., Tani, H. & Hirano, T.  (2010). Detection of fire impact and vegetation recocery over tropical peat swap forest by satellite data and ground-based NDVI instrument. *International Journal of Remote Sensing*, *31* (20), 5297-5314.

Shakesby, R.A., & Doerr, S.H., 2006. Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews 74*, 269–307.

Smith, A.M.S, Drake, N.A., Wooster, M.J., Hudak, A.T., Holden, Z.A., & Gibbons, C.J., (2007). Production of Landsat ETM+ reference imagery of burnt areas within Southern African savannahs: comparison of methods and application to MODIS. *International Journal of Remote Sensing*, *28*, 12, 2753-2775.

Solans Vila J.P. & Barbosa P. (2010). Post-fire vegetation regrowth detection in the Deiva Marina region (Liguria-Italy) using Landsat TM and ETM+ data. *Ecological Modelling* 2I21 p.75–84.

Steyaert, L., Hall, F., & Loveland, T., (1997). Land cover mapping, fire regeneration, and scaling studies in the Canadian boreal forest with 1 km AVHRR and Landsat TM data. *International Journal of Geophysical Research 102*, 29581–29598.

Stueve, K., Cerney, D., Rochefort, R., & Kurt, L., (2009). Post-fire tree establishment patterns at the alpine treeline ecotone: Mount Rainier National Park, Washington, USA. *Journal of Vegetation Science, 20*, 107–120.

Sunee, S., Hussin, Y. A., & de Gier, A. (2001). Assessment of forest recovery after fire using Landsat TM images and GIS techniques: a case study of Mae Wong national park, Thailand. In *ACRS Proceedings of the 22nd Asian Conference on Remote Sensing ACRS, Singapore*.

Vapnik, V. (1995): *The nature of statistical learning theory*, New York, NY: Springer-Verlag.

Veraverbeke, S., Somers, B., Gitas, I., Katagis, T., Polychronaki, A., & Goossens, R. (2012). Spectral mixture analysis to assess post-fire vegetation regeneration using Landsat Thematic Mapper imagery: accounting for soil brightness variation. *International Journal of Applied Earth Observation and Geoinformation*, *14*(1), 1-11.

Veraverbeke, S., W. W. Verstraeten, S. Lhermitte & R. Goossens (2010). Evaluating Landsat Thematic Mapper spectral inidices for estimating burn severity of the 2007 Peloponnese wildfires in Greece. *International Journal of Wildland fire*, *19*, 558-569.

Viedma, O., Meliá, J., Segarra, D., & García-Haro, J. (1997). Modeling rates of ecosystem recovery after fires by using Landsat TM data. *Remote Sensing of Environment*, *61*, 383–398.

White, J.D., K.C. Ryan, C.C. Key, % S.W. Running, (1996). Remote sensing of forest fire severity and vegetation recovery. *International Journal of Wildland Fire*, *6*(3):125–136.

Wittenberg, L., Malkinson, D., Beeri, O., Halutzy, A., & Tesler, N. (2007). Spatial and temporal patterns of vegetation recovery following sequences of forest fires in a Mediterranean landscape, Mt. Carmel Israel. *Catena*, *71*(1), 76-83.

***Highlights (for review)**

**Subject:** Research Highlights of submitted paper

1. Investigate ecosystem recovery dynamics following a fire event occurred in a Mediterranean region, exploiting free distributed EO imagery and GIS analysis techniques.

2. Explore the spatio-temporal relationships of re-growth dynamics under the burn scar to topographical characteristics of the fire-affected area.

3. Findings can be helpful in restoration efforts taking place in the affected area, that being a setting of high ecological, environmental and cultural importance for the local community and not only.

4. Our work contributes to the understanding Mediterranean landscape dynamics, and corroborates the practical usefulness of EO technology and GIS as an effective tool in policy decision making and successful landscape management, potentially as an operation service solution.

Figure

## List of Figures:

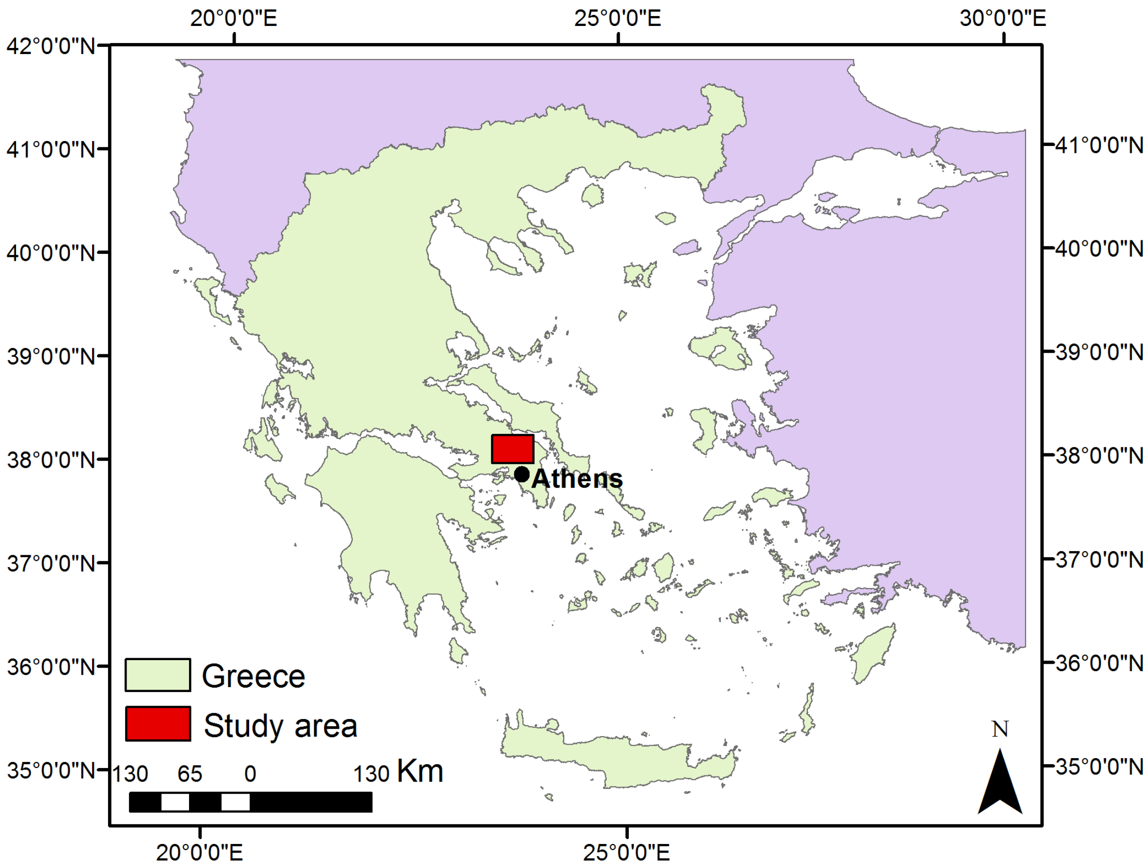


**Figure 1:** *Study area location in Greece (indicated by the red colored box)*

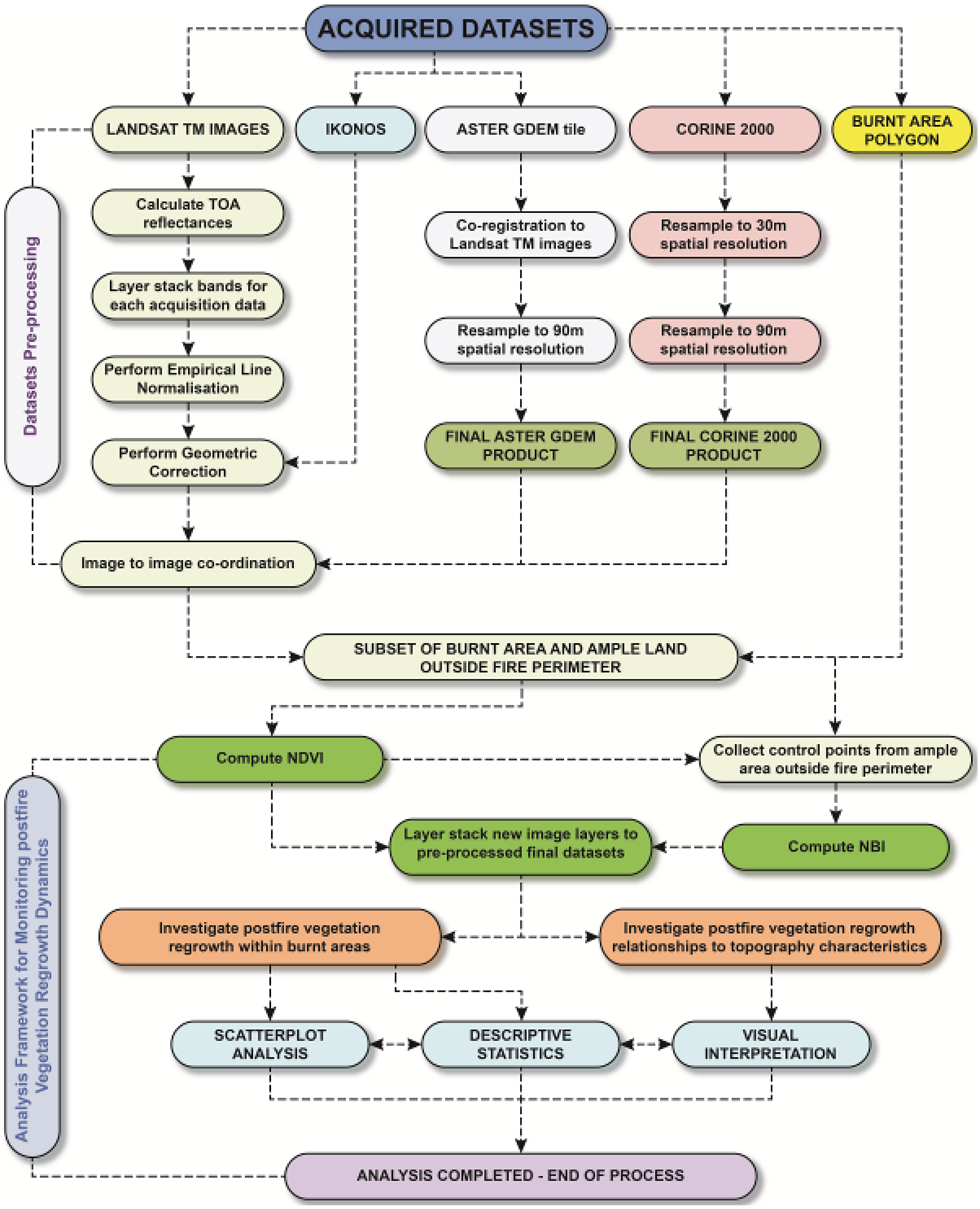


**Figure 2:** *Overall methodology implemented in our study for analyzing the regrowth dynamics of the studied region using the TM data.*

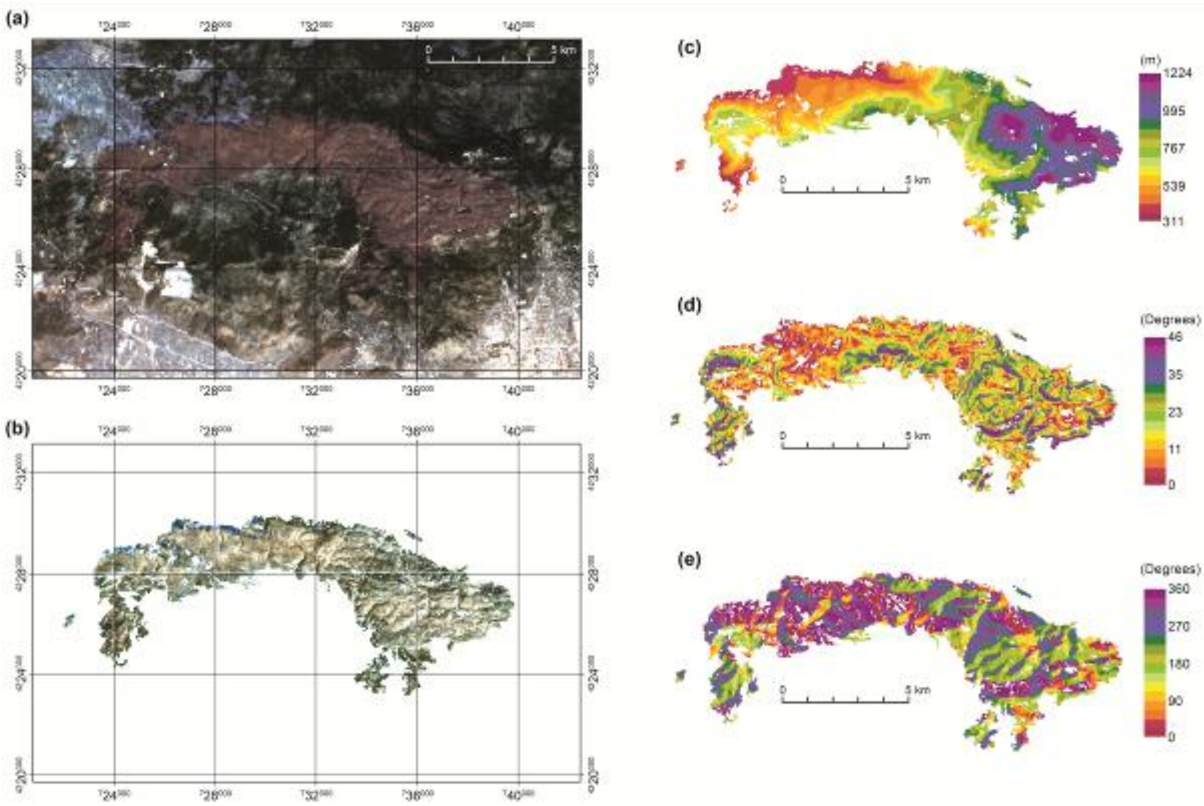

**Figure 3:** *An illustration of some key datasets derived upon completion of the pre-processing steps. From left to right: a) the initial subset of the study area on the TM image acquired on July 3rd, 2000, (b) the masked area inside the burnt area envelope for the same image, (c)elevation and (d) aspect maps of the area covered by the burnt area envelop derived from ASTER Global Digital Elevation (GDEM) product.*

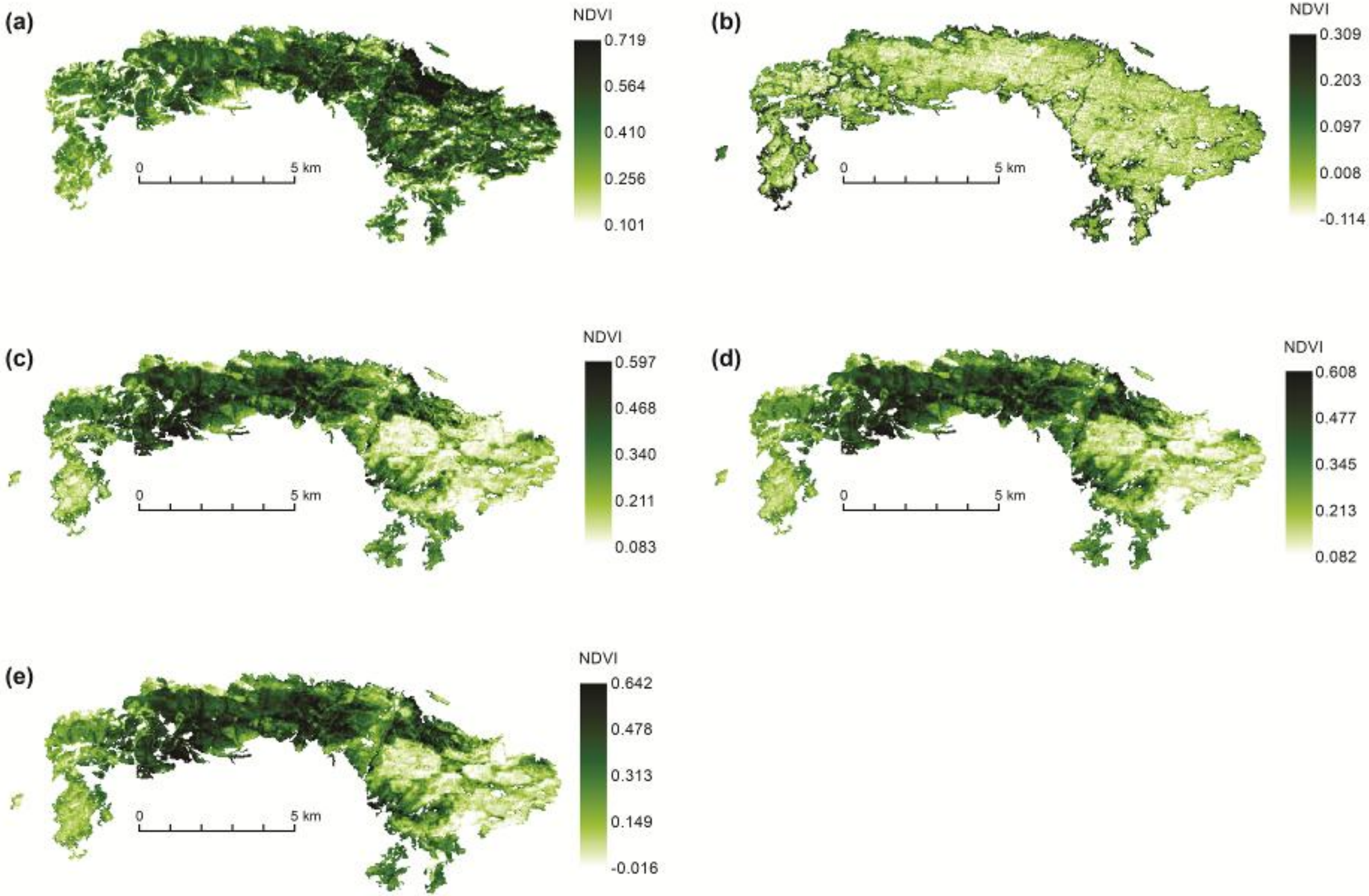


**Figure 4:** *NDVI maps computed from the pre-processed Landsat TM images: (a) May $16^{th}$, 2007, (b) July $3^{rd}$, 2007, (c) July 24, 2009, (d) August $13^{th}$,, 2010 & and (e) August $15^{th}$, 2011. The variation in the NDVI ranges between the different days of observation is evident.*

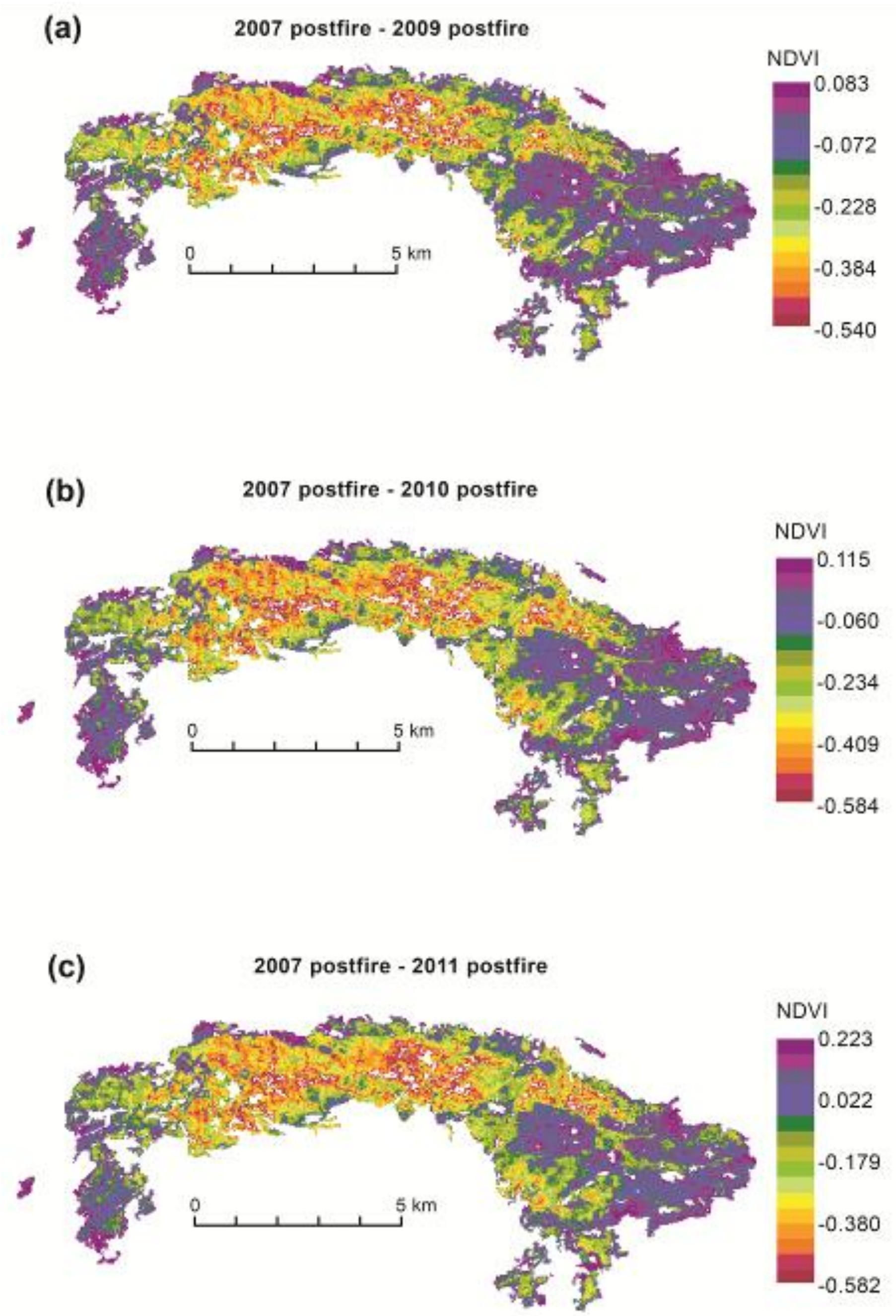


**Figure 5:** *NDVI difference maps for the area under the burn scar, here between the post fire image in 2007 and all TM images after the fire suppression.*

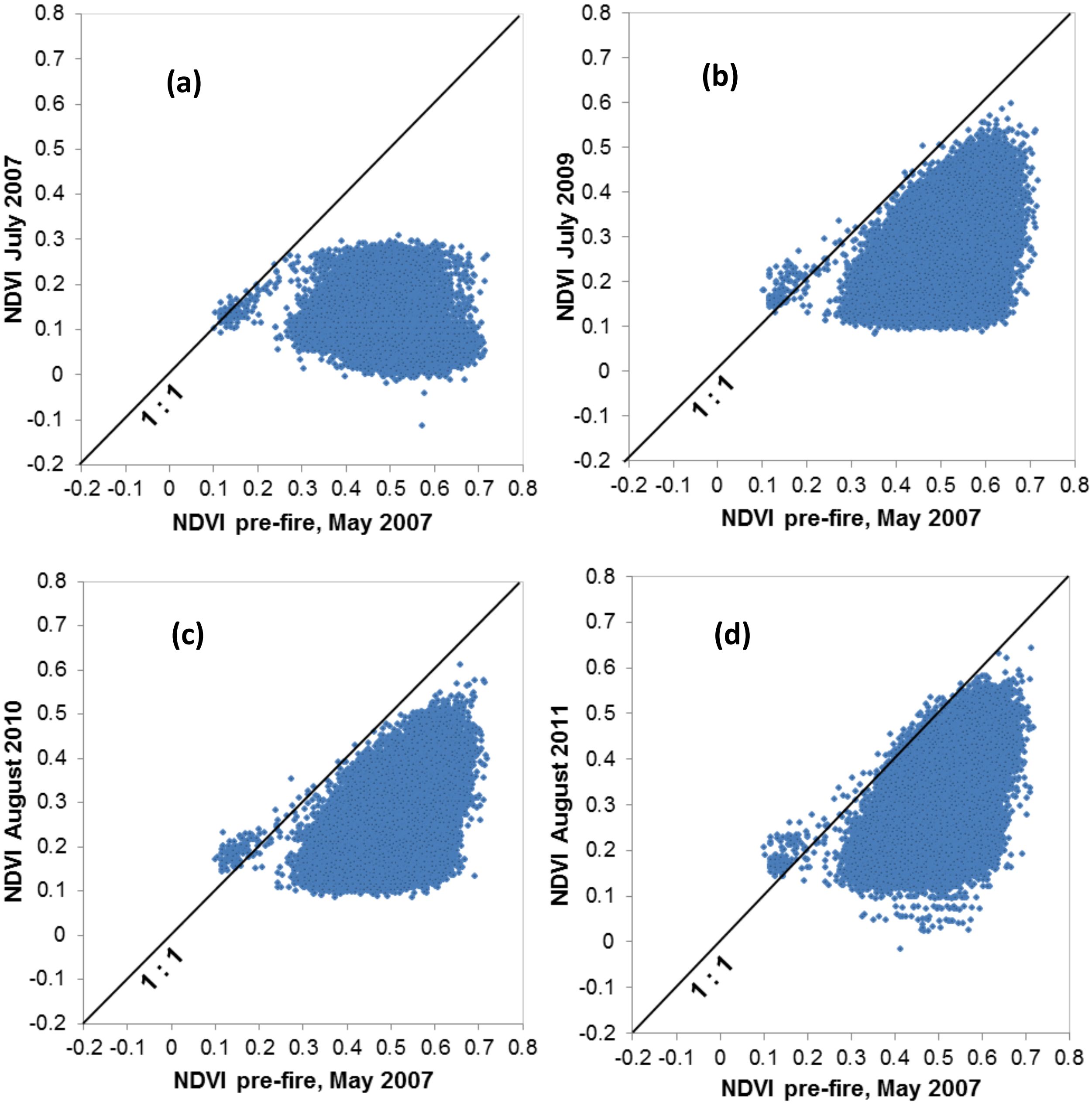


**Figure 6:** *Scatterplots of pre-fire NDVI (May 2007) against (a) post-fire July 2007 (b) July 2009, (c) August 2010 and (d) August 2011. It can be observed the gradual increase of the slope to pre-fire conditions, which is suggesting re-growth in the area.*

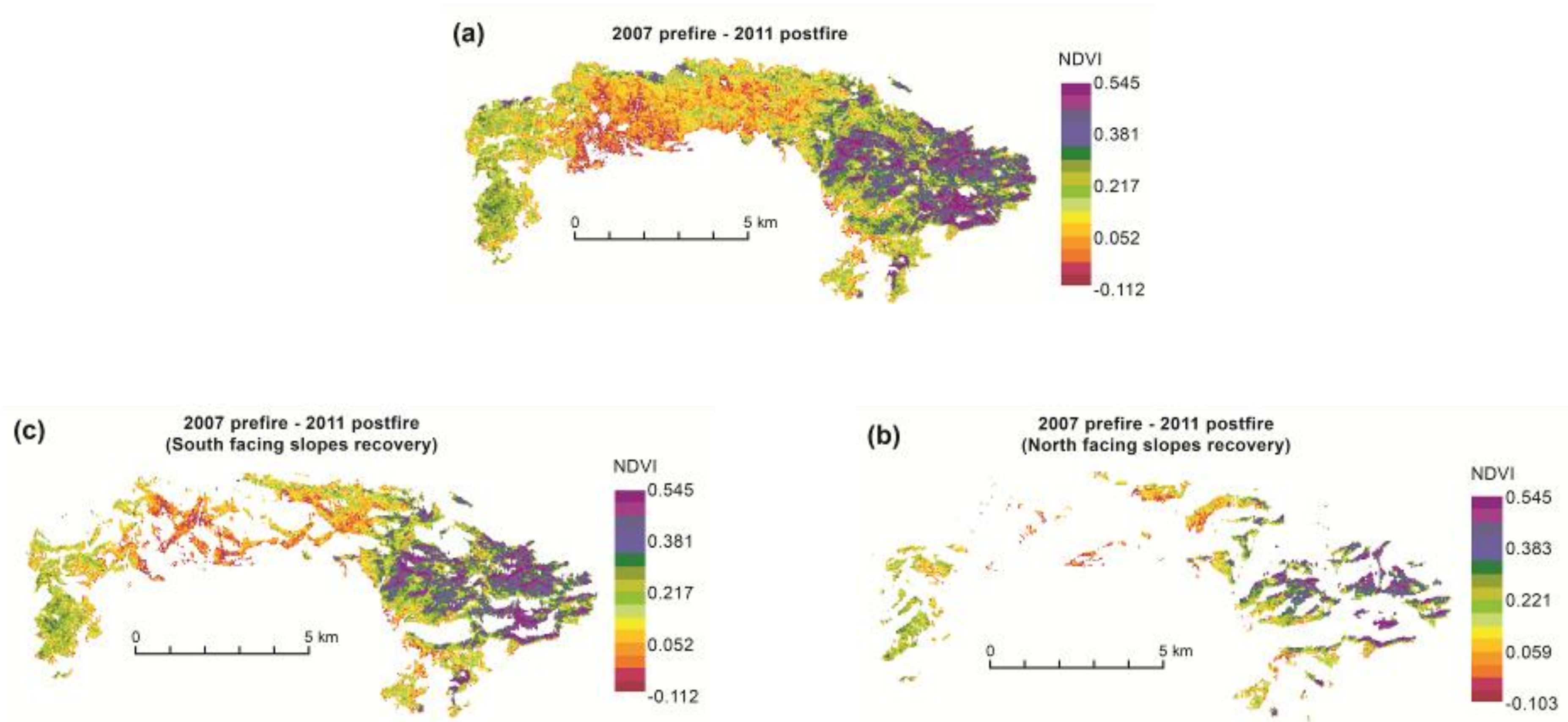


**Figure 7:** *NDVI difference maps for the area under the burn scar, here between the pre-fire image and the most recent postfire image acquired in 2011 for a) the entire study area b) north facing slopes only and (c) south facing slopes only.*

## List of Tables:

**Table 1:** *NDVI changes for the area under the burn scar*

| | NDVI | | | |
|---|---|---|---|---|
| **Landsat TM image date** | **Min** | **Max** | **Mean** | **Stdev** |
| 16/05/2007 | 0.101 | 0.789 | 0.499 | 0.071 |
| 03/07/2007 | -0.114 | 0.309 | 0.087 | 0.052 |
| 24/07/2009 | 0.083 | 0.597 | 0.259 | 0.092 |
| 12/08/2010 | 0.082 | 0.608 | 0.264 | 0.090 |
| 15/08/2011 | -0.016 | 0.642 | 0.298 | 0.097 |

**Table 2:** *Scatterplot and correlation/regression analysis of the NDVI before and after the fire event for the whole area under the burn scar*

| Period | Slope | Intercept | $R^2$ |
|---|---|---|---|
| **May 2007-July 2007** | -0.215 | 0.194 | 0.086 |
| **May 2007-July 2009** | 0.495 | 0.012 | 0.148 |
| **May 2007 – August 2010** | 0.567 | - 0.019 | 0.202 |
| **May 2007-August 2011** | 0.630 | - 0.017 | 0.215 |

**Table 3:** *NDVI changes for the area under the burn scar, separately for: (A): north facing, and, (B) south facing slopes.*

| | NDVI | | | |
|---|---|---|---|---|
| **(A).** | **North facing slopes only** | | | |
| **Landsat TM image date** | **Min** | **Max** | **Mean** | **Stdev** |
| 16/05/2007 | 0.104 | 0.716 | 0.515 | 0.069 |
| 03/07/2007 | -0.114 | 0.295 | 0.085 | 0.052 |
| 24/07/2009 | 0.099 | 0.597 | 0.300 | 0.090 |
| 12/08/2010 | 0.087 | 0.608 | 0.302 | 0.088 |
| 15/08/2011 | 0.095 | 0.622 | 0.340 | 0.094 |
| **(B).** | **South facing slopes only** | | | |
| **Landsat TM image date** | **Min** | **Max** | **Mean** | **Stdev** |
| 16/05/2007 | 0.116 | 0.719 | 0.478 | 0.070 |
| 03/07/2007 | -0.015 | 0.295 | 0.087 | 0.050 |
| 24/07/2009 | 0.083 | 0.526 | 0.218 | 0.077 |
| 12/08/2010 | 0.090 | 0.538 | 0.224 | 0.077 |
| 15/08/2011 | 0.026 | 0.582 | 0.253 | 0.083 |

**Table 4:** *Scatterplot and correlation/regression analysis of the NDVI before and after the fire event separately for the north and south facing slopes only*

| Period | Slope | Intercept | $R^2$ |
|---|---|---|---|
| **May 2007-July 2007** | | | |
| North facing | -0.239 | 0.2090 | 0.103 |
| South facing | -0.205 | 0.185 | 0.081 |
| **May 2007-July 2009** | | | 0.171 |
| North facing | 0.537 | 0.023 | 0.103 |
| South facing | 0.356 | 0.048 | |
| **May 2007 – August 2010** | | | 0.253 |
| North facing | 0.641 | - 0.028 | 0.125 |
| South facing | 0.392 | 0.037 | |
| **May 2007-August 2011** | | | 0.276 |
| North facing | 0.716 | - 0.030 | 0.139 |
| South facing | 0.445 | 0.042 | |